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LARGE ANGLE MAGNETIC SUSPENSION TEST FIXTURE

By

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Progress Report
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SUMMARY

Good progress is being made in several major areas. These include eddy current modelling and analysis, design optimization methods, wind tunnel Magnetic Suspension and Balance Systems (MSBS), payload pointing and vibration isolation systems, and system identification. In addition, another successful International Symposium has been completed, with the Proceedings being printed at the time of writing.

These activities continue current work under this Grant and extend previous work on magnetic suspension systems and devices in the Guidance and Control Branch and will permit the demonstration of several new developments in the field of magnetic suspension technology.

REVIEW OF CURRENT AND ONGOING WORK

(i) Eddy current modelling. The ELEKTRA computer code has been used to calculate forces, stored energy, field magnitude and phase, and power losses for magnetic suspension (LAMSTF-like) and magnetic bearing (ASPS-like) configurations. Various problems have been encountered and overcome, such that an analysis capability suitable for application to the LGMSS project is steadily emerging. Validation and testing specific to the LGMSS application will commence shortly. Some of this work has been published, with future publication possible.

(ii) Design optimization. An effort to apply state-of-the-art optimization methods and computer codes to the magnetic suspension problem has begun. Initial analysis has concentrated on small-gap, axisymmetric bearings. It has been shown that optimum designs based on maximum force, minimum power, etc., are identifiable and are distinctly different from each other. This effort will result in a publication at some point in the future. Analysis will then proceed to the large-gap problem, which is more challenging, although some work has already been accomplished (David Cox, LaRC).

(iii) Wind Tunnel Magnetic Suspension and Balance Systems. There appears to be renewed interest in this application, both in general, and for a specific test objective, namely ultra-high Reynold's number testing. A presentation relating to the latter has already been made, with a copy attached as an Appendix to this report. A presentation relating to the former is planned for the AIAA Aerospace Sciences meeting in January 1997. A copy of the abstract is also attached as an Appendix.

(iv) Annular Suspension and Pointing System. Work continues at a low level, following successful levitation in five degrees-of-freedom. The control software has been "cleaned up" and some electrical upgrades made to reduce noise. A joint Proposal for future work with LaRC and Boeing is under consideration and would result, if successful, in a dramatic increase in effort in this area.

(v) System Identification. For identifying a dynamic system, operating under a stochastic environment, projection filters, which were originally derived for deterministic systems, are developed by using optimal estimation theory. This newly developed system identification algorithm is successfully implemented at NASA Lanlgey Research Center for identification of unstable large-gap magnetic suspension systems. The results show that it can be applied for dynamic systems with known or unknown feedback dynamics. The test data processed can be either in the time domain or frequency domain. It is also very effective in controller design for nonlinear unstable systems and for direct Kalman filter gain estimation without knowing noise covariances.

(vi) Symposium support. Support is being provided for the organization and execution of the 3rd International Symposium on Magnetic Suspension Technology.

PROBLEM AREAS

The Federal furloughs significantly impacted the pace of work on-site at NASA. There appears to have been little financial impact, although some doubts remain.

PRESENTATIONS and PUBLICATIONS

Britcher, C.P.; Groom, N.J.: Computational analysis of static and dynamic behaviour of magnetic suspensions and magnetic bearings. 3rd International Symposium on Magnetic Suspension Technology, Tallahassee, Florida, December 1995.

Neff, D.; Britcher, C.P.: Design and implementation of a digital controller for a vibration isolation and vernier pointing system. 3rd International Symposium on Magnetic Suspension Technology, Tallahassee, Florida, December 1995.

Britcher, C.P.: Application of Magnetic Suspension and Balance Systems to Ultra-High Reynolds Number Facilitites. Workshop on Ultra-High Reynolds Number Flows. Brookhaven National Laboratory, June 1996. (presented by Robert A. Kilgore).

Britcher, C.P.: Application of Magnetic Suspension Technology to Large Scale Facilities. Accepted for presentation at AIAA Aerospace Sciences Meeting, Reno, NV, January 1997.

Cox, D.E.; Groom, N.J.; Hsiao, M.H.; Huang, J.K.: Modling and identification of a large gap magnetic suspension system. 3rd International Symposium on Magnetic Suspension Technology, Tallahassee, Florida, December 1995.

Hsiao, M.H.; Huang, J.K.; Cox, D.E.: Iterative LQG controller design through closed-loop identification. ASME Journal of Dynamic Systems, Measurement and Control, June 1996.

Huang, J.K.; Hsiao, M.H.; Cox, D.E.: Indirect identification of linear stochastic systems with known feedback dynmaics. AIAA Journal of Guidance, Control and Dynmaics, July/August 1996.

Lee, H.C.; Hsiao, M.H.; Huang, J.K.; Chen, C.W.: Identification of stochastic system and controller via projection filters. ASME Journal of Vibration and Acoustics, August 1996.

Huang, J.K.; Lee, H.C.; Scoen, M.P.; Hsiao, M.H.: State-space system identification from closed-loop frequency response data. Accepted for AIAA Journal of Guidance, Control and Dynamics.

Preprint

Application of Magnetic Suspension and Balance Systems to Ultra-High Reynolds Number Facilitites

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Abstract

The current status of wind tunnel magnetic suspension and balance system development is briefly reviewed. Current technical work at NASA Langley Research Center is detailed, where it relates to the ultra-high Reynolds number application. The application itself is addressed, concluded to be quite feasible, and broad design recommendations given.

Introduction

Wind tunnel Magnetic Suspension and Balance Systems (MSBS) have been under continuous investigation and development since 1957. A significant number of small-scale systems have been constructed and a variety of aerodynamic testing carried out [1]. This paper will briefly review the previous work in wind tunnel MSBSs and will examine the 8 known systems currently in operational condition or undergoing recommissioning. The ultra-high Reynolds number application will then be addressed in some detail, focusing on specific technical issues wherever possible. Technical developments currently emerging from research programs at NASA and elsewhere will be reviewed briefly, where there is potential impact on the ultra-high Reynolds number application. Finally, some opinions based on the author's experience will be given.

Wind Tunnel Magnetic Suspension and Balance Systems

An aerodynamic test model can be magnetically suspended or levitated in the test section of a wind tunnel (Figure 1). The classical approach involves the use of a ferromagnetic core in the model, either soft iron or permanent magnet material, with the applied fields generated by an array of electromagnets surrounding the test section. This arrangement is always open-loop unstable in at least one degree-of-freedom, so the position and attitude of the model is continuously sensed, with the electromagnet currents adjusted via a feedback control system to maintain stability and the desired position/orientation (Figure 2). Optical sensing systems of various types have been prevelant, although electromagnetic and X-ray systems have also been used. Electromagnet power amplifers typically require modest bandwidths, but high reactive power capacity. The resulting system is referred to as a Magnetic Suspension and Balance System (MSBS), since aside from the suspension/levitation function, whole-body forces and moments can be recovered from calibrations of the electromagnet currents.

The governing equations for this type of suspension system (following notation in [2]) are as follows :

$$\vec{F}_c \simeq \forall \, (\vec{M}.\nabla \vec{B_o}) \qquad \vec{T}_c \simeq \forall \, (\vec{M} \times \vec{B_o})$$

- where $\vec{M}$ represents the magnetization of the magnetic core in A/m, $\vec{B}$ the applied magnetic field in Tesla, $\forall$ is the volume of the magnetic core in m^3, and the subscript o indicates that the field or field gradient is evaluated at the centroid of the magnetic core. Now, following the detailed development presented in reference 2, the effect of changes in relative orientation between the magnetic core and the electromagnet array can be incorporated as follows :

$$\vec{F}_c = \forall \ [T_m][\partial B][T_m]^{-1} \vec{M} \qquad \vec{T}_c = \forall \ \vec{M} \times \ [[T_m] \vec{B}]$$

Where a bar over a variable indicates magnetic core coordinates, $[\partial B]$ is a matrix of field gradients and $[T_m]$ is the coordinate transformation matrix from electromagnet coordinates to suspended element (magnetic core) coordinates. Study of the torque equation reveals that it is only possible to generate 2 components by this "compass needle" phenomena with a single magnetization direction. This gives rise to the well-known "roll control" problem in wind tunnel MSBSs, where the magnetization direction has usually been along the long axis of the magnetic core, in turn along the axis of the fuselage.

In wind tunnel applications, the primary motivation for MSBSs has been the elimination of the aerodynamic interference arising from mechanical model support systems [3]. The fact that the suspended model forms part of a feedback control system inherently permits predetermined motions of the suspended model to be created rather easily. This suggests great potential for studies of unsteady aerodynanic phenomena, although the potential has not been fully exploited at this time (see later Section).

It should be noted that the configuration discussed above is not the only possibility. Inherently stable configurations are feasible, such as by using a.c. applied fields, or by inclusion of diamagnetic materials in various ways. Laboratory suspensions using these techniques have been demonstrated for many years [4], but not in the wind tunnel application. A major disadvantage has been the difficulty of arranging significant passive damping of unwanted motions. The feedback controlled approach relies on artificial damping, whose value is limited principally by the control algorithm and the power supply capacity.

A Perspective on Ultra-High Reynolds Number Tunnels

So that the rest of this paper be set in proper context, the author's perspective on the ultra-high Reynolds number tunnel development effort will now be presented.

Research has been underway for several years examining the possibility of constructing an ultra-high Reynolds number "wind" tunnel, concentrating on the use of liquid or gaseous helium as the working fluid. At one point, the tunnel was referred to by some researchers as the "infinite Reynolds number" wind tunnel, since operation with superfluid helium was contemplated and a promise of effectively zero viscosity of the working fluid was held out. Current work appears to be focused on slightly more modest performance (finite Reynolds number!) but could still result in a facility with a Reynolds number capability one order of magnitude higher than anything currently existing. With these more modest objectives, the option of employing gaseous helium as the working fluid becomes quite viable, as has been suggested many times over the years [5].

The engineering application is clearly to hydrodynamic studies of submersibles, with the particular item of interest perhaps being wake-related signature reduction. Fundamental studies of high Reynolds number turbulence are also attracting some interest. It has been assumed that an MSBS would be mandatory for this type of facility, since a conventional support system would create severe problems by corruption of the vehicle's wake. Application of MSBS technology to this problem was reviewed in the 1989 Workshop [6].

Current MSBS Activity Worldwide

NASA Langley Research Center 13-inch MSBS

This system, illustrated in Figure 3, is currently inactive, although remains in operational condition. It comprises a low-speed wind tunnel, 5 uncooled copper electromagnets, 4 with iron cores, bipolar thyristor power supplies, an optical model position sensing system with a minicomputer-based digital controller. The system has been used for a variety of drag studies of axisymmetric and near-axisymmetric geometries, as well as support interference evaluations. Support interference increments of up to 200% have been discovered, although this is hardly typical [7,8].

The ODU 6-inch MSBS

If this system were to be described as the ODU/NASA/MIT 6-inch system, then its history and identity would be clear to all workers in the MSBS field. The electromagnet assembly and low-speed wind tunnel, illustrated in Figure 4, from the original MIT "6-inch" MSBS [9,10] has found its way to Old Dominion University, and partial recommissioning is currently in progress. A unique feature is the use of electromagnetic position and attitude sensing. Here, the suspended model forms the core of a high frequency variable differential transformer. It is planned to restore the system to full operation with new power supplies and a digital control system.

International Efforts

The National Aerospace Laboratory in Japan currently operates the largest MSBS ever constructed, with a test section 60 cm square (roughly 2 feet). Together with a smaller system (15 cm), current research is focusing on rapid force and moment calibration procedures [11]. Researchers in Taiwan have recently completed construction of a small (10 cm) system and are commencing low-speed wind tunnel tests [12]. Russian activity is at a low level, but includes studies of data telemetry systems from suspended models. One MSBS remains operational, at MAI/TsAGI [13]. Low-density, high Mach number aerodynamic measurements are continuing at Oxford University in England with their nominally 7.5 cm system [14]. A recent development has been the discovery of a new system at the National University of Defense Technology in P.R. China, about which information is just becoming available.

Table 1 - "Operational" MSBSs, 1996

Organization	Approx Size[1]	Application	Status
NASA LaRC	13-inch	Low-speed drag, R&D	Inactive
ODU	6-inch	System R&D	Recommissioning
Oxford Univ.	3-inch	Hypersonic aerodynamics	Active
MAI/TsAGI, Moscow	15-inch	System R&D	Inactive
NAL, Japan	4-inch	System R&D	Active
NAL, Japan	23-inch	System R&D	Active
NCKU, Taiwan	6-inch	System R&D	Active
NUDT, P.R. China	6-inch	System R&D	Active

New Technology

A program has been underway for some years at NASA Langley Research Center to develop technology for large-gap applications of magnetic suspensions. Applications include, but are not limited to, wind tunnel MSBSs, space payload pointing and vibration isolation systems, momentum storage and control

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[1]Square-root of wind tunnel test section cross-sectional area

devices, maglev trains and electromagnetic launch systems. Emphasis has been placed on the development of formalized dynamic models and the application of modern controller design techniques. Two small laboratory scale levitation systems have been constructed, with air-gaps between suspended element and electromagnets of 10 cm [15,16]. The first system is referred to as the Large-Angle Magnetic Suspension Test Fixture (LAMSTF) and is capable of 360-degree rotation of the levitated model about a vertical axis (Figure 5). Levitation here implies the use of magnetic forces of repulsion from below the test object, rather than the more traditional approach of attractive forces from above, or some combination. The second system, currently unnamed, utilizes a pair of concentric coils carrying steady currents, to provide a background force opposing gravity. An important novel feature is the use of a transversely magnetized permanent magnet core in the cylindrical suspended element. The magnetization direction is vertical is this application. This configuration, illustrated in Figure 6, provides full six degree-of-freedom control capability with passive stability in vertical translation and two rotations. The third rotation (about the vertical axis) is neutrally stable, and the remaining two translations (in the horizontal plane) are slightly unstable. A secondary array of electromagnets ("control" coils) provides stability and the capability for predetermined motions. A larger system of comparable configuration, the Advanced Controls Test Facility, is close to completion, with a 1 meter air-gap [17]. This system includes superconducting coils to provide the background levitation force, with water-cooled copper control coils. It will represent the largest, large-gap magnetic suspension or levitation device ever constructed.

It should be realized that the tranversely magnetized magnetic core configuration is well suited to the wind tunnel application, where generation of magnetic roll torque has already been mentioned as being a long-standing problem. Using vertically magnetized permanent magnet cores within an aircraft model's fuselage would provide roughly equal (and large) pitch and roll torque capability. Lift, drag and sideforce capability will be largely unaffected compared to the conventional axial magnetization configuration. Only yaw torque is relatively reduced, although it is observed that aerodynamic yaw torques are seldom dominant. The additional torque is generated by a term of the form :

$$\vec{T}_z \simeq \Psi \int_\Psi \vec{M}_z \left\{ \frac{\partial B_y}{\partial z} x \right\}$$

This can be non-zero if the core geometry is suitably chosen and $\frac{\partial}{\partial x}\left[\frac{\partial B_y}{\partial z} \right]$ is non-zero.

It can also be noted that magnetic suspension and levitation technology has made dramatic progress in other applications in recent years. Feedback-controlled magnetic bearings for rotating machinery applications are a viable commercial item [18], with a growing number of companies involved and regular International Symposia [Zurich,1988, 1994, Tokyo, 1990, Alexandria, 1992]. Useful spin-offs from this work include specialized control hardware, algorithms and software, new sensing approaches, improved system modelling and analysis, and application of High Temperature Superconductors (HTS) to current-controlled electromagnets. Maglev "trains" are on the verge of revenue-generating operation, with sophisticated prototypes in operation in Germany and Japan. The German approach relies on feedback controlled copper electromagnets generating attractive levitation forces from below the "guideway" (track); the Japanese approach utilizes superconducting electromagnets generating repulsive levitation forces by inducing eddy currents in the guideway. Both approaches have a speed capability in excess of 300 m.p.h. The U.S. National Maglev Initiative (now defunct) spawned a range of design studies, with the Grumman Corporation hybrid magnet design perhaps notable.

Preliminary Considerations for MSBS Application to Ultra-High Reynolds Number Facilities

The magnitude of the engineering challenge is determined primarily by the test requirements and the choice of working fluid. By way of example, three design points have been chosen for a 10:1 length-to-diameter ratio quasi-axisymmetric, low-drag model. The target length Reynolds number is 10^9. Numerical values are derived largely from data in reference 6. The model weight is estimated based on

the weight of a steel or permanent magnet magnetic core occupying around 50% of the available volume. The drag force is estimated based on a drag coefficient (C_D) of 0.1.

	Gaseous Helium	Helium I	Helium II
Temperature, K	5.3	2.8	1.6
Velocity, m/s	40	10	4
Unit Reynolds No., m^{-1}	3×10^8	3.8×10^8	4.4×10^8
Dynamic pressure, Pa	8725	7150	1160
Model length, m	3.3	2.63	2.27
Test section size, m	0.94 square	0.75 square	0.65 square
Max. model weight, N	8700	4400	2830
Drag force, N	74.6	38.9	4.7

The immediate conclusion is that this application is extremely benign from a force perspective. The likely aerodynamic/hydrodynamic forces appear to be a small fraction of the deadweight of the model. This fact justifies some attention to passively stable suspensions in this application [such as 19]. Increasing attention is being paid to this possibility by the magnetic bearing community and progress is being made, although many difficulties remain to be solved [20].

Some Opinions and Observations

The first consideration for this application is the extremely low temperature. Whatever the working fluid, the MSBS must either be designed for an environment around 2-4 K, or the test section must be designed such that the MSBS is essentially "outside" the cold zone. The latter approach was taken with the only MSBS to be used with a cryogenic wind tunnel to date [21]. It is thought, however, that the former would be preferable in this application, due to the extreme penalty in cooling power incurred should the thermal insulation of the test section be compromised. Immediately one might be concerned that the power dissipation of the suspension electromagnets might negate this advantage, but a.c. capable low-temperature and high-temperature superconducting coils have been demonstrated [22]. HTS coils are perhaps the first choice, since they would be operated well below their transition temperature, providing huge stability margins and permitting considerable flexibility in design of cooling and insulation systems. The d.c. and a.c. field requirements in this application appear to be extremely modest compared to "conventional" wind tunnel MSBSs, suggesting no great problems in electromagnet or power supply design or procurement.

Two approaches for position and attitude sensing are viable, optically-based and the electromagnetic position sensor (EPS, [9]). Optoelectronic devices can operate effectively at 2-4 K, but there are practical concerns relating to condensation of stray gases etc. For this reason, and also due to the perception that the typical model to be tested is naturally quasi-axisymmetric, and does not seem likely to be oriented at extreme angles relative to the test section axis, the EPS is recommended as a first choice. The electromagnetic behaviour of this system should be essentially temperature independent.

The ferromagnetic core of the model could be either soft iron or permanent magnet. It is known that either will operate without difficulty down to liquid nitrogen temperature, in fact exhibiting improved properties. Operation at the extremely low temperatures anticipated would have to be researched. There seems little point in resorting to the persistant superconducting solenoid model core [21,23] since the force requirements seem so modest. The purpose of this core design was to provide higher force capability in high dynamic pressure wind tunnel applications.

An important design issue is thought to be the selection of materials for the test section. First, the EPS must be located "inside" any electrically conducting structural shells. Further, it has been found that eddy

currents in conducting material close to the suspension electromagnets can significantly degrade the system dynamics [24]. Due to the low electrical conductivity of metals at the extremely low temperatures encountered here, this problem is likely ot be severe. Pending further study, it is therefore recommended that designs concentrate on the use of electrically non-conducting materials. It should be noted that passively stable suspension systems usually rely on eddy currents for damping of unwanted motions. Again, due to the low conductivities in this application, further study will be required.

Specialized Aerodynamic Testing

"Static" aerodynamic testing can be defined as where the model's geometric axis is fixed in space and with respect to the freestream velocity vector. This class of testing includes, but is not limited to, drag measurements. "Dynamic" testing is also of great significance in many cases, but is very challenging with mechanical model supports, and is usually done only sporadically. MSBSs of the feedback controlled type have long been recommended as a powerful altenative approach, since arbitrary model motions can be commanded rather easily through the feedback control system. At least three research teams have addressed dynamic testing with MSBSs over the years, though none recently. At MIT [9,25] and the University of Southampton [26,27], forced oscillation testing has been successfully carried out. The University of Virginia developed a special design of MSBS specifically for dynamic stability work [28,29] and conducted limited testing. With more modern control and data acquisition approaches, small-amplitude forced oscillation testing in an MSBS should be a quite viable test technique. A single facility could make measurements requiring an array of conventional mechanical rigs.

The suspension of models through large ranges of angles-of-attack has been demonstrated in wind tunnels [21] and through large ranges of orientation in other laboratory facilities [15]. This can now be considered rather standard practice. Based on the authors understanding of the application of the ultra-high Reynolds number facility, this possibility is not further emphasized here.

Acknowledgements

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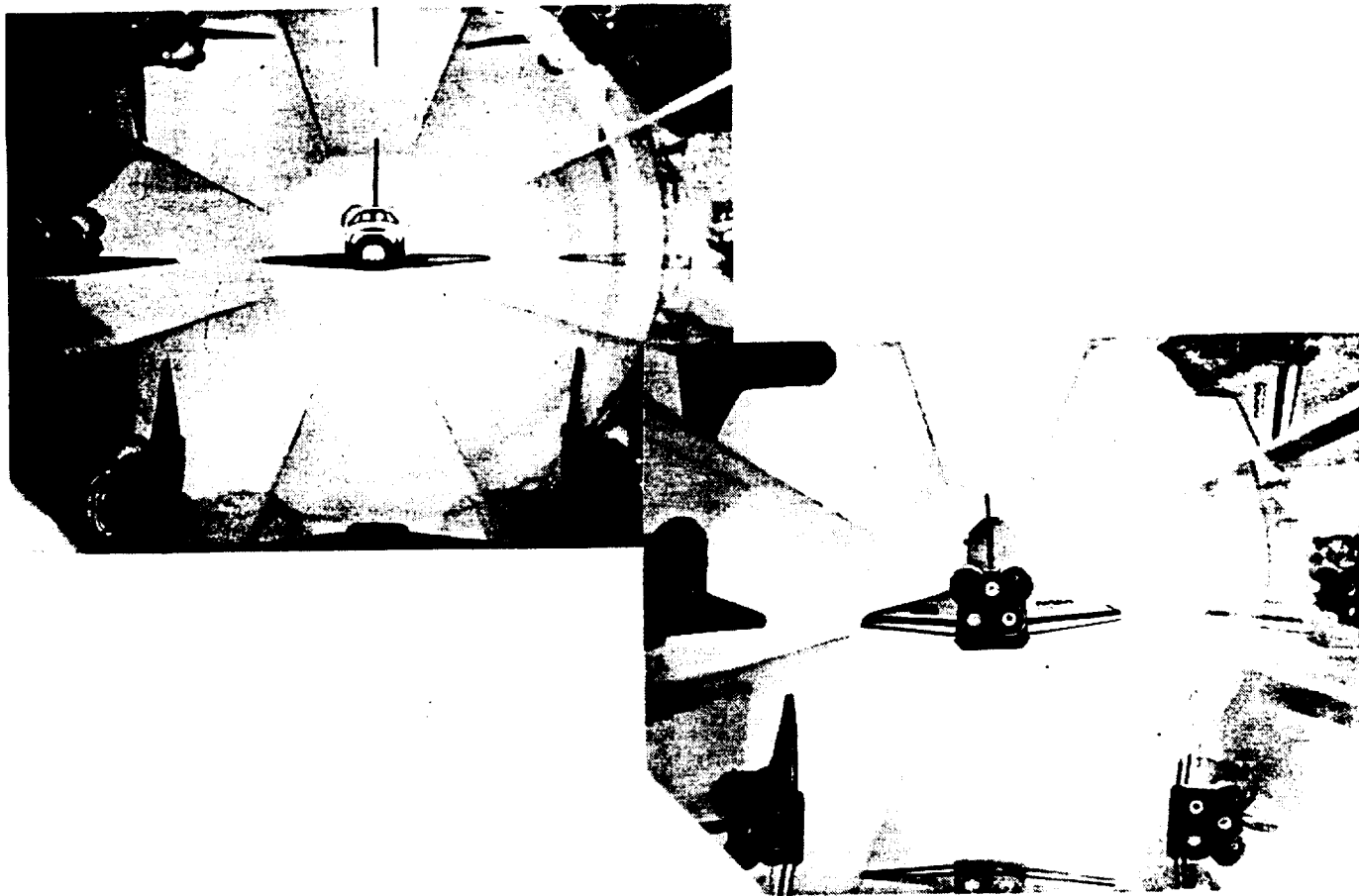
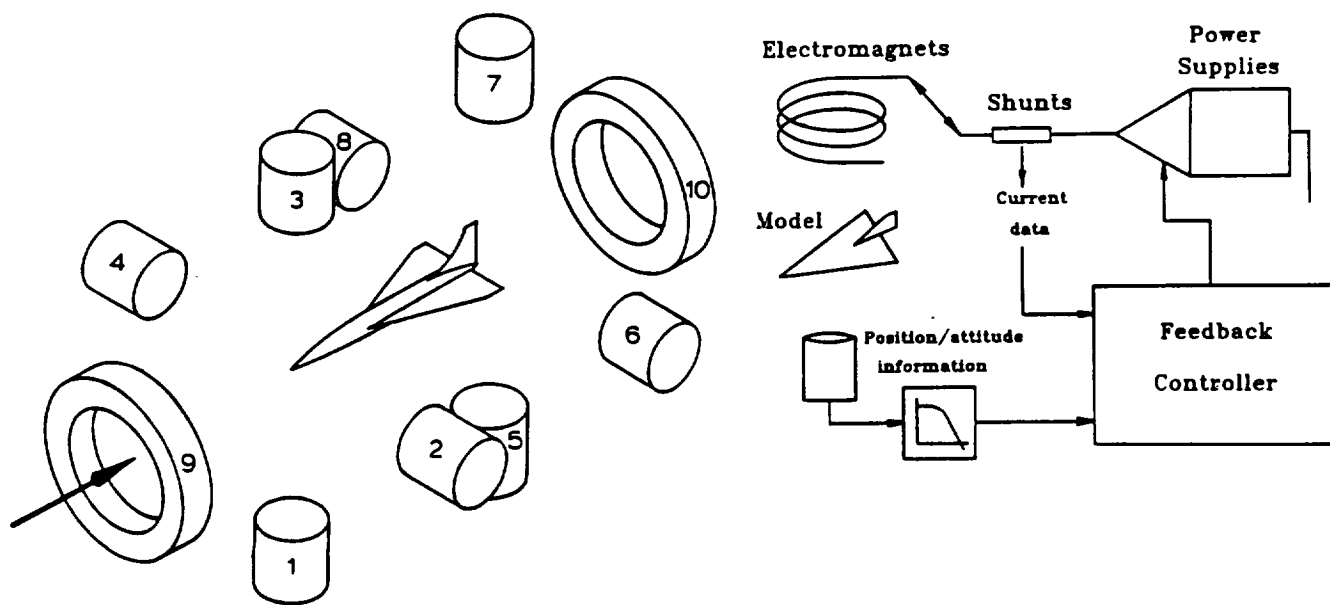Figure 1 - Wind Tunnel Magnetic Suspension and Balance System (ODU 6-inch MSBS)

Figure 2 - Generic Configuration and System Block Diagram for a Wind Tunnel MSBS

Power
Supplies

Fan

Detail of electromagnet configuration

Electromagnets
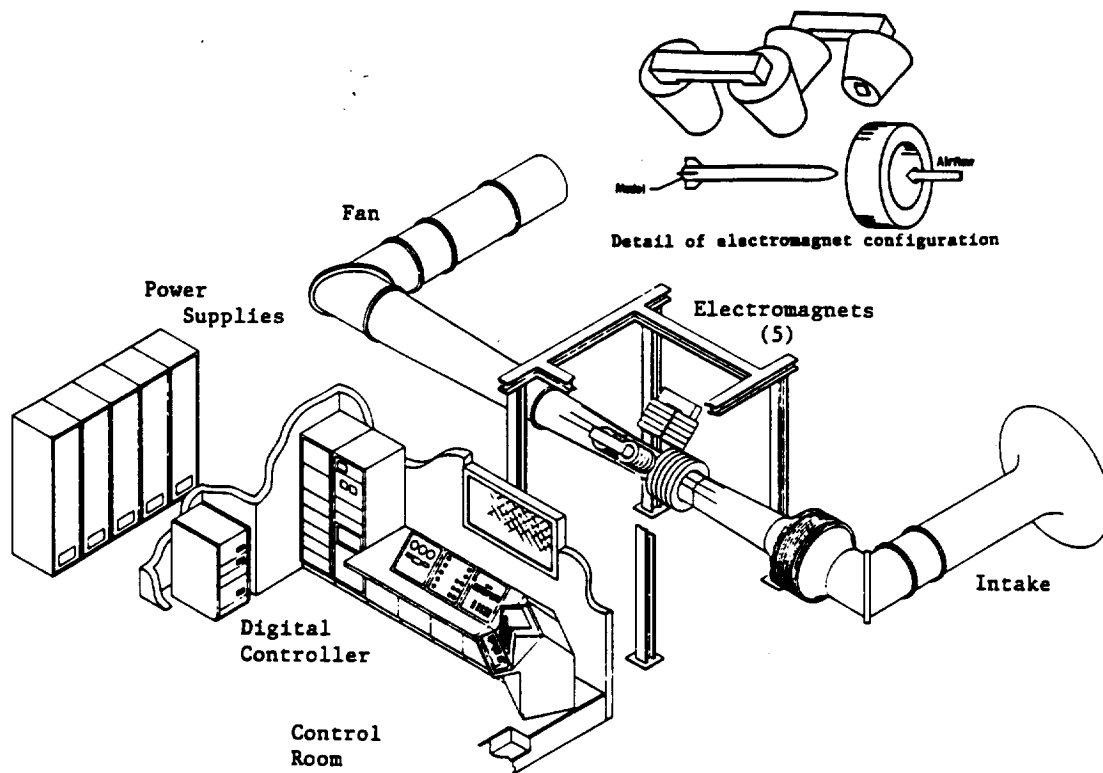(5)

Digital
Controller

Control
Room

Intake

Figure 3 - The NASA Langley 13-inch Magnetic Suspension and Balance System
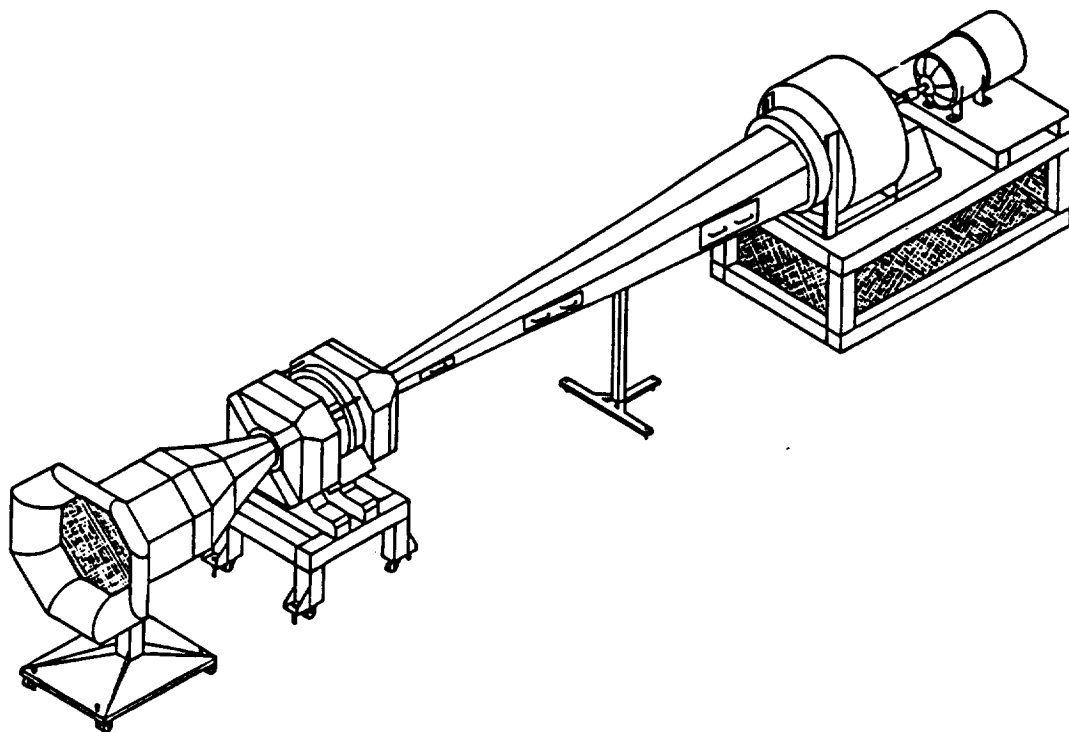
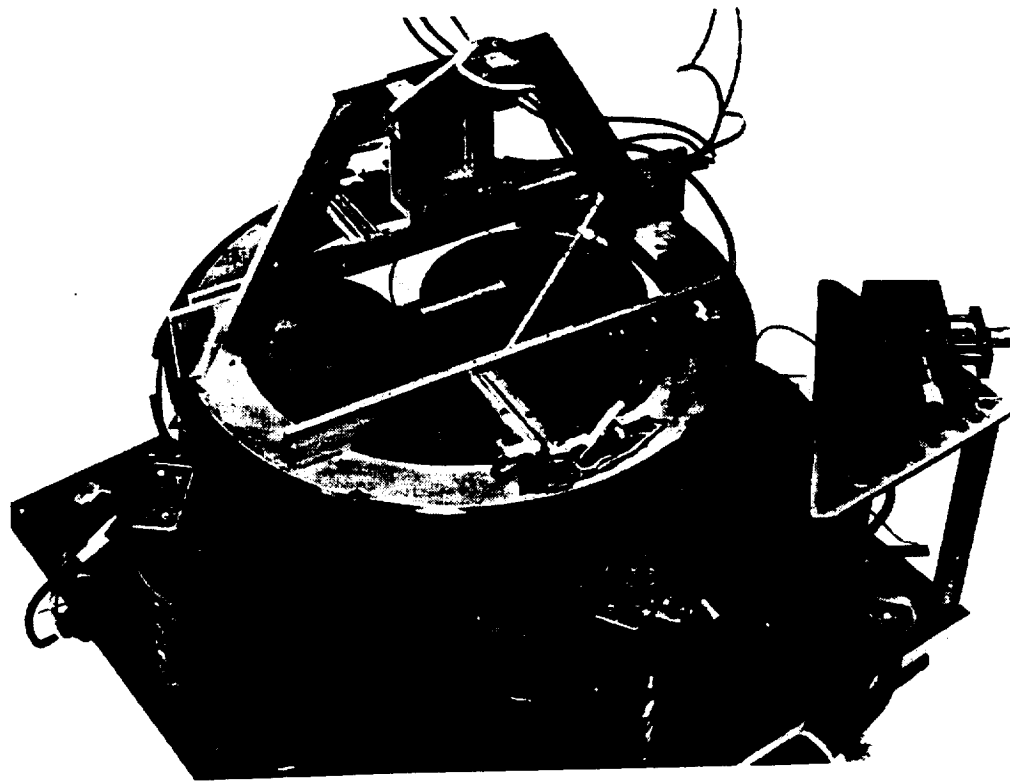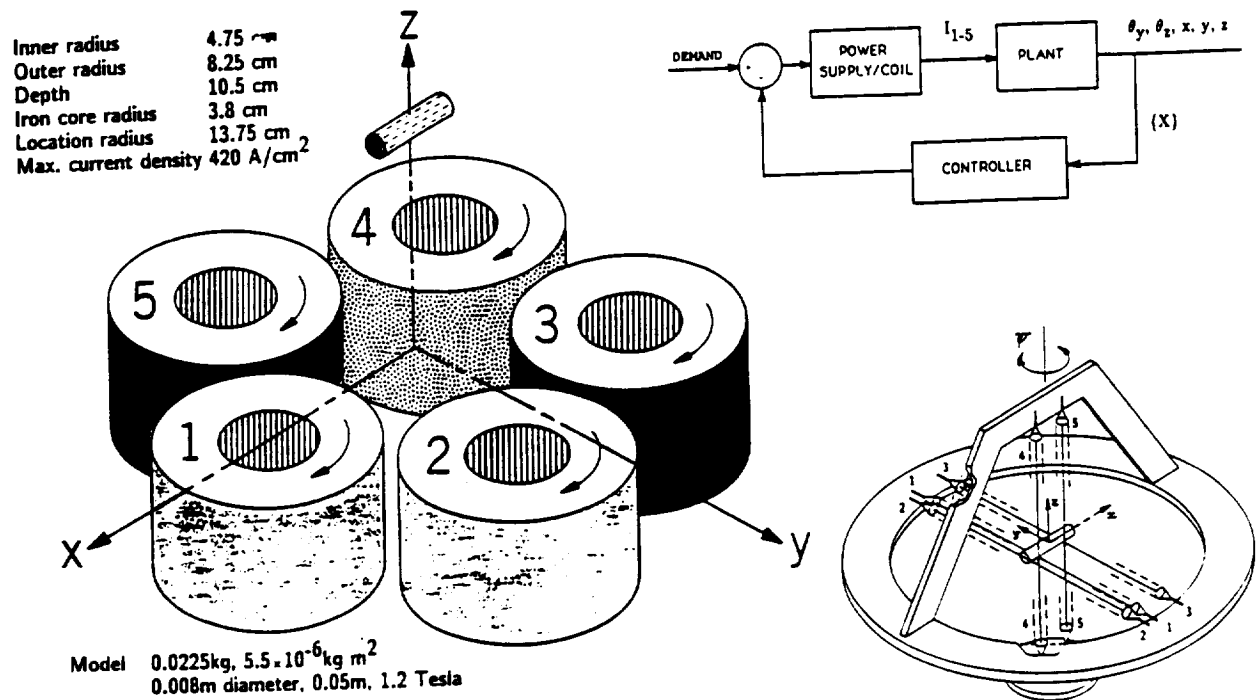Figure 4 - The ODU/NASA/MIT 6-inch Magnetic Suspension and Balance System

Inner radius   4.75 cm
Outer radius   8.25 cm
Depth   10.5 cm
Iron core radius   3.8 cm
Location radius   13.75 cm
Max. current density 420 A/cm^2

Model   0.0225kg, 5.5 x 10^{-6}kg m^2
        0.008m diameter, 0.05m, 1.2 Tesla

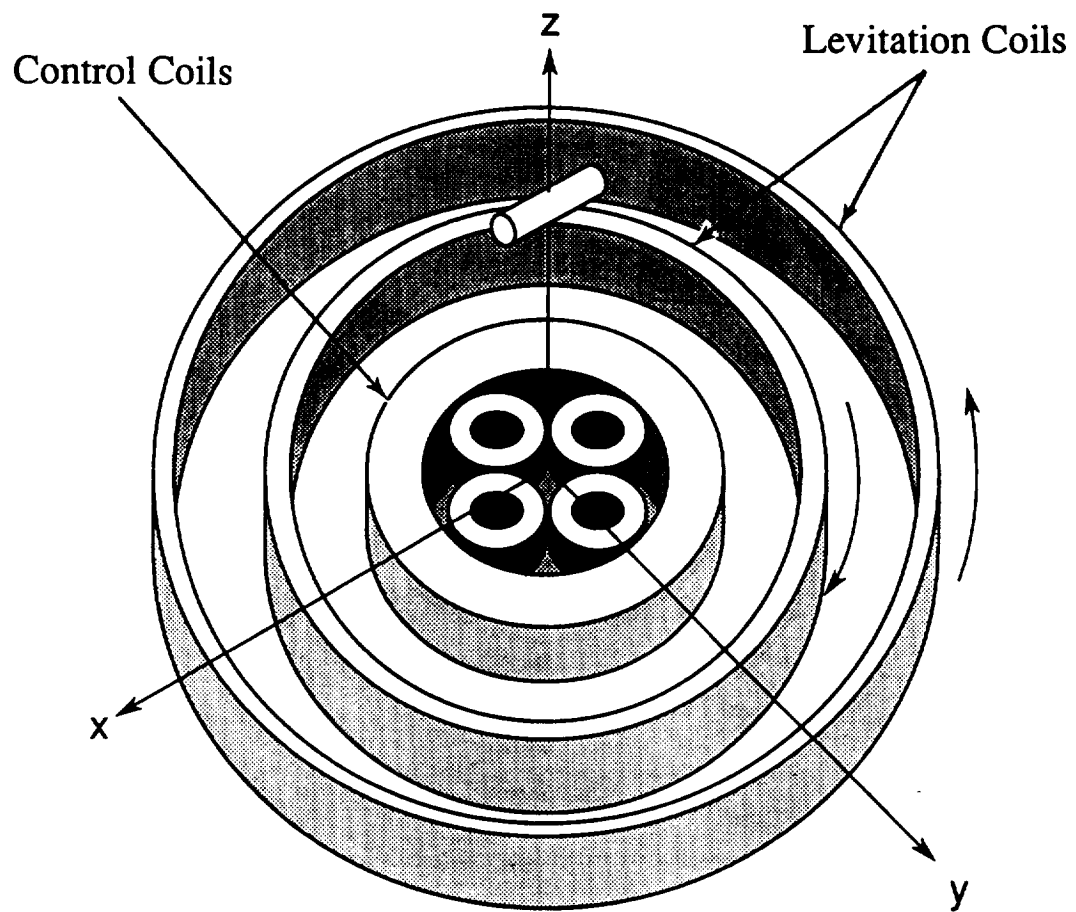Figure 5 - The NASA LaRC Large Angle Magnetic Suspension Test Fixture

Figure 6 - A 6 degree-of-freedom Electromagnet Configuration (from [17])

Application of Magnetic Suspension Technology to Large Scale Facilities - progress, problems and promises

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Introduction

Wind tunnel Magnetic Suspension and Balance Systems (MSBS) have been under investigation and development since 1957. A significant number of small-scale systems have been constructed and a variety of aerodynamic testing carried out [1]. Current work in the U.S. is limited, but includes a serious investigation of an application for an ultra-high Reynolds number wind tunnel, a modest system recommissioning effort, and is benefiting from a variety of "spin-off's" from generic large-gap magnetic suspension development work at NASA Langley Research Center. Other work on MSBSs is currently known to be proceeding in Japan, Taiwan, P.R. China, England and Russia. This paper will briefly review the previous work in wind tunnel MSBSs and will examine the 8 systems currently in operational condition or undergoing recommissioning. The ultra-high Reynolds number application will be addressed in some detail. Technical developments emerging from research programs at NASA and elsewhere will be reviewed briefly, where there is potential impact on large-scale MSBSs. The potential aerodynamic applications for large MSBSs will be addressed. Finally, some opinions on the usefulness and feasibility of a large MSBS will be given.

Current U.S. efforts

Ultra-High Reynolds Number Liquid Helium Tunnel

Research has been underway for several years examining the possibility of constructing an ultra-high Reynolds number "wind" tunnel with liquid helium as the working fluid [2]. At one point, the tunnel was referred to by some researchers as the "infinite Reynold's number" tunnel, since operation with superfluid helium was contemplated and a promise of effectively zero viscosity of the working fluid was held out. Current work appears to be focussed on slightly more modest performance (finite Reynold's number!) but could still result in a facility with a Reynold's number capability one order of magnitude higher than anything currently existing. The engineering application is clearly to hydrodynamic studies

of submersibles, with the particular item of interest being wake-related signature reduction. Fundamental studies of high Reynolds number turbulence are also attracting interest. It has been assumed that an MSBS would be mandatory for this type of facility, since a conventional support system would create severe problems by corruption of the vehicle's wake. Research is proceeding, with recent completion of a preliminary design and the hosting of a second workshop [3,4].

The ODU 6-inch MSBS

If this system were to be described as the ODU/NASA/MIT 6-inch system, then its history and identity would be clear to all workers in the MSBS field. The electromagnet assembly and low-speed wind tunnel from the original MIT "6-inch" MSBS [5,6] has found its way to Old Dominion University, and is currently in process of partial recommissioning. A unique feature is the use of electromagnetic position and attitude sensing. It is planned to restore the system to full operation with new power supplies and a digital control system.

International Efforts

The National Aerospace Laboratory in Japan currently operates the largest MSBS ever constructed, with a test section 60 cm square (roughly 2 feet). Together with a smaller system (15 cm), current research is focussing on rapid force and moment calibration procedures [7]. Researchers in Taiwan have recently completed construction of a small (10 cm) system and are commencing low-speed wind tunnel tests [8]. Russian activity is at a low level, but includes studies of data telemetry systems from suspended models. One MSBS remains operational, at TsAGI [9]. Low-density, high Mach number aerodynamic measurements are continuing at Oxford University in England with their nominally 15 cm system. A recent development has been the commissioning of a new system at the National University of Defense Technology in P.R. China, about which information is just becoming available.

Table 1 - "Operational" MSBSs, 1996

Organization	Approx Size	Application	Status
NASA LaRC	13-inch	Low-speed, R&D	Inactive
ODU	6-inch	System R&D	Recommissioning
Oxford Univ.	3-inch	Hypersonic aerodynamics	Active
MAI/TsAGI, Moscow	18-inch	System R&D	Inactive
NAL, Japan	4-inch	System R&D	Active
NAL, Japan	23-inch	System R&D	Active
NCKU, Taiwan	6-inch	System R&D	Active
NUDT, P.R. China	6-inch	System R&D	Active

New Technology

A program has been underway for some years at NASA Langley Research Center to develop technology for large-gap applications of magnetic suspensions. Applications

include, but are not limited to, wind tunnel MSBSs, space payload pointing and vibration isolation systems, momentum storage and control devices, maglev trains and electromagnetic launch systems. Two small laboratory scale levitation systems have been constructed, with air-gaps between suspended element and electromagnets of 10 cm [10,11]. A larger system of comparable configuration, the Advanced Controls Test Facility, is close to completion, with a 1 meter air-gap [12]. This system includes superconducting coils to provide the background levitation force, with water-cooled copper control coils. It will represent the largest, large-gap magnetic suspension or levitation device ever constructed.

An important novel feature is the use of a transversely magnetized permanent magnet core in the cylindrical suspended element. This provides full six degree-of-freedom control capability. It has subsequently been realized that this configuration is well suited to the wind tunnel application, where generation of magnetic roll torque has been a long-standing problem. Using vertically magnetized permanent magnet cores within the fuselage provides roughly equal (and large) pitch and roll torque capability. Lift, drag and sideforce capability will be largely unaffected compared to the conventional axial magnetization configuration. Only yaw torque is relatively reduced, although it is observed that aerodynamic yaw torques are seldom dominant.

Aerodynamic Test Requirements and Capabilities

A fresh look at the inherent capabilities of MSBSs and perceived shortcomings in conventional wind tunnel test capability was recently undertaken [13]. The main points will be summarized here, with the important rider that they should be taken to represent only the personal views of this author.

The large system design studies undertaken in the 1980's, under the direction of NASA Langley Research Center, concentrated on application to an NTF-type wind tunnel. The main technical justification was the elimination of support interference, which is a major problem around the transonic regime. Design studies were made for large-scale systems by General Electric Company [14] and Madison Magnetics Incorporated [15,16,17]. The conclusions were that a very large system was technically feasible, though quite expensive. A major cost driver was the unsteady (control) force and torque requirement, producing large cryogen boil-off in conventional superconducting electromagnets.

It seemed (and indeed is) inevitable that the cost of a "large MSBS" would be a significant fraction of the cost of the wind tunnel in which it would be used. The system under consideration would have provided static aerodynamic data, free of support interference, but little else. The technical risk was perceived to be quite high, since the system would have been around 5 times larger in linear dimension than anything previously attempted (c.1985, NAL 23-inch system and NASA LaRC ACTF not yet completed). The design was ultimately seen as constituting an insufficiently attractive program and work gradually slowed and eventually was stopped, in or around 1990.

Provision of an support interference-free aerodynamic test capability is a valuable goal and should be pursued. However, the precise application needs to be carefully considered. For instance, while there is no doubt that support interference is major problem in the accurate evaluation of cruise drag in wind tunnel testing, there exist strategies for its assessment, such as mounting normally sting-mounted models on blade, wing-tip or fin supports [18]. This is an expensive process, but it is difficult to construct a persuasive argument this should be replaced by another apparently expensive process (MSBS). Valuable generic data could, however, be generated at moderate Reynolds numbers in a smaller and less expensive facility. Some interesting information was generated using the 13-inch MSBS at LaRC, which included a demonstration of the fact that the drag correction for sting interference could be as high as 200% (though admittedly not typical, see [19,20]). It has also been known for some time that support interference can be particularly significant in cases where the support lies in a separated and/or unsteady wake or any type of vortex flows [21,22]. The understanding of high angle-of-attack and unsteady aerodynamics would be greatly improved by the provision of interference-free test data, especially with the possibility of including fully representative model motions, such as wing rock. The fundamental research to permit the use of MSBSs at high angles-of-attack has been done, and suspension at extreme attitudes has been demonstrated, but the systems have not yet been applied to this type of testing.

An Opinion

It seems that a strong argument can be made that the original program focus was flawed, insofar as the "cost-benefit ratio" for a system focused largely on support interference elimination in static testing was never favorable. Instead, it is now argued that the focus should be on the areas of unsteady aerodynamics and dynamic stability, where conventional test facilitites are arguably quite deficient. The unique ability of MSBSs to permit controlled motion through arbitrary trajectories (limited only by force and moment capability) represents an enormous untapped potential.

Acknowledgements

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